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A.A. Kon'kov and A.P. Ryazin

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ABSTRACT: To obtain reliable data on the spectral characteristics of air at high temperatures, the parameters of the shock tube used must first be set accurately. Several tests are made to determine the optimal conditions for producing a powerful shock wave with a stable velocity. The equipment and methods used for the spectrographic analysis of the characteristics of air are described. Finally, the experimental findings are compared with calculated indices for the absorption coefficients of air at various temperatures, showing satisfactory agreement between experimental and calculated data.

At the present time, there are no reliable experimental data /13* on the spectral characteristics of air at temperatures above 12,000°K, a situation caused by the difficulties of holding air at such temperatures with explicitly known parameters. The basic instrument in this case is the shock tube. However, a calculation of the state of the gas behind the shock wave at velocities above 8 km/sec according to experimental theory cannot be assumed to be correct in this case, apparently, since an important role is played by the processes which lead to energy dissipation (radiational cooling, the influence of a boundary layer). In this article we will attempt an experimental investigation of the possibilities of obtaining, in a shock tube shock, wave velocities above 6 km/sec, and then attempt to use it as an instrument to obtain a gas with known parameters under those conditions.

Parameters of the Shock Tube

In the experiments we used a shock tube which allowed us to obtain shock wave velocities of up to 10 km/sec. In its construction the shock tube consisted of a high pressure section (with a length of 1500 mm and a diameter of 30 mm) and a low pressure section (with a length of 3800 mm and a diameter of 30 mm). The two sections were divided by a copper diaphragm (the instrument is described in more detail in [1]).

According to [2], the maximum possible shock wave velocity is determined by the relationship

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* Numbers in the margin indicate pagination in the foreign text.

$$U = \frac{\gamma_1 + 1}{\gamma_4 - 1} \cdot a_4,$$

where γ_1, γ_4 are the specific heat ratios in the high low pressure sections.

Consequently, with strictly equal conditions in attaining high shock wave velocities it is desirable to have in the high pressure chamber a gas which has the lowest possible molecular weight at the highest possible temperature. A most effective method for increasing shock wave velocity is that of heating the gas in the high pressure chamber using an electric discharge or using an oxygen-hydrogen mixture with a hydrogen excess or diluted with helium as a propelling gas. According to [2, 3], the latter method allows us to increase the shock wave velocity by a factor of two or three compared to the situation in which hydrogen is used in the high pressure chamber. However, the data from the literature on this question are somewhat contradictory. The calculation given in [3], assuming the heating of the oxygen-hydrogen mixture with helium as a diluent (OHHM) takes place at a constant volume, showed that it is possible /14 to increase the shock wave velocity by 70-80% in comparison to the systems usually used when hydrogen is used as the "propelling" gas. Reference [4] showed that the experimentally-used shock wave velocities, obtained when OHHM was used as the "propelling" gas, are significantly greater than those calculated on the assumption of heating at constant volume. The experimental points are grouped around the curve computed for the ratio of sound velocity in the high and low pressure sections $a_4/a_1 = \infty$, while on the assumption of heating at constant volume $a_4/a_1 \simeq 6$. The authors of [4] note that the shock wave velocity varies in a direction opposite to the pressure change of the rupture of the diaphragms, so that a shock wave of maximum velocity under strictly equal conditions is formed when the diaphragm ruptures directly after the mixture is ignited. Based on these experiments, the authors come to the conclusion that heating of the mixture at constant pressure is the most effective way to obtain the highest possible shock wave velocities. No detonation wave arose in these experiments.

The authors of [5] demonstrated that the most effective method is to use diaphragms whose rupture pressure is roughly half the maximum pressure generated when the OHHM is heated at constant volume.

In relation to the problem stated we should first clarify under what conditions shock wave velocities of 8-10 km/sec can be obtained which are relatively stable and can be reproduced from experiment to experiment. To determine the optimal conditions for obtaining the most powerful shock wave in the high pressure chamber we varied the initial pressure and composition of the OHHM and also the strength of the diaphragms. The experiments showed that helium dilution of the heating mixture, according to [2, 3], increases shock wave velocity. However, helium dilution above 65-70% does

not significantly alter wave velocity. A helium dilution of 75-80% creates a situation in which ignition cannot be initiated at all in the mixture. Later experiments were conducted with OHHM at a helium dilution of 65-70%. Varying the initial pressure of the OHHM in the high pressure section from 1 to 30 atm showed [2-4] that under strictly equal conditions, the shock wave velocity increases and the uncontrolled variance in the velocity of the latter decreases as the pressure increases. A subsequent increase in pressure (above 40 atm) was not possible because of the structural characteristics of the shock tube.

The strength of the diaphragms was varied from 30 to 90 atm at constant OHHM composition and initial pressure. The strength of the diaphragms was gradually increased up to the point at which the maximum pressure generated with OHHM heating was not sufficient to rupture the diaphragm. It was discovered that, for example, with an initial OHHM pressure of 14 atm this limit is (90 ± 5) atm. According to [3] the maximum pressure after heating must be equal to 140 atm. Thus it follows that when the OHHM is heated there is only a seven-fold increase in pressure rather than ten-fold.

Figure 1 shows the experimental data with an initial air pressure in the low pressure section of 5 mm Hg and an initial OHHM pressure of 29 atm. Plotted along the ordinate axis are the experimentally measured values of the velocities of the incident shock waves, and along the abscissa are the pressure ratios in which p is the pressure required to rupture the diaphragm and p_1 is 5 mm Hg.

The shock wave velocity was determined by two methods. The /15
first method consists of measuring the time required for the shock wave to cross the distance between two ionization sensors. The second method consists of measuring the time required for the shock wave to cross the distance between an ionization sensor and a viewing screen, i.e., the time between two pulses coming from an ionization sensor and a photoelectric multiplier. The accuracy of the velocity measurements was ± 3%. Within the margin of error of the measurements, both methods yielded identical results. The same figure shows the curves of the function relating the shock wave and the pressure (generated in the high pressure section), computed according to the elementary theory [3].

Curve (1) corresponds to the computed [3] values of a_4. In our calculation of curve (2) we used values for the velocity of sound in the high pressure section which were two times greater than the data of [3].

It follows from the data shown in Figure 1 that with a diaphragm rupture pressure of 90 atm, the maximum (for a given OHHM composition) shock wave velocities of 8-10 km/sec have already been attained. Velocities of 10 km/sec were rarely encountered. A further increase in the strength of the diaphragms did not lead to any significant increase in shock wave velocity. The second important

experimental finding which follows from the data of Figure 1 is that the experimentally measured values for velocity are significantly larger than the computed values [Curve (1)]. This fact agrees with the data of [4] and does not contradict the data of [5], which found experimentally that the maximum velocities of the shock wave were obtained when the maximum pressure generated in the high pressure section was twice as great as the pressure at which the diaphragms ruptured.

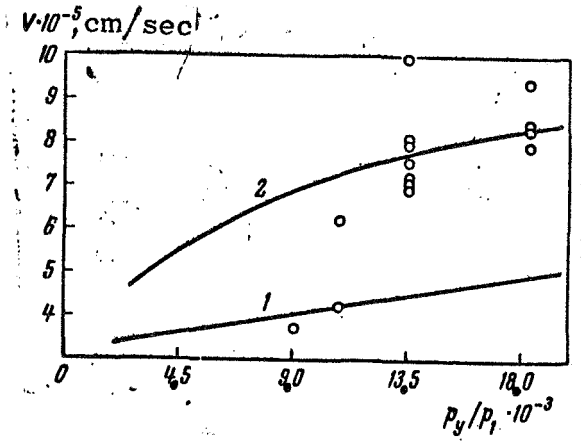

Fig. 1. Shock Wave Velocity as a Function of the Ratio of Pressures on the Diaphragm: (1) a_4/a_1 = 6; (2) a_4/a_1 = 12.

If we consider that in this case the maximum pressure in the high pressure section (noting the comment made above) is about 200 atm, then, consequently, according to [2] the most powerful waves must be generated with diaphragm rupture pressures of 100 atm. This situation was observed in the experiment, but we were not able to detect any shock wave velocities above 10 km/sec.

The fact that the experimentally observed shock wave velocities exceeded the calculated velocities can be understood if we bear in mind that as a basis of the calculation [3] we assumed an idealized system of the processes which take place in the high pressure section, and in particular that the heating process in this section takes place at a constant volume.

In reality, apparently, one of the following cases may occur [6].

The detonation wave which forms ruptures the diaphragm.

Rupture of the diaphragm takes place after the detonation wave /16 reflects off the diaphragm and the gas located between the diaphragm and the reflected wave begins to flow out.

The reflected wave reflects off the front of the flame and the diaphragm ruptures after the arrival of this doubly reflected wave.

No detonation wave is formed. A shock wave is formed in front of the flame front. After this shock wave reflects off the diaphragm, a detonation wave forms and then the diaphragm ruptures.

Neither a detonation wave nor a shock wave forms; the perturbations which travel from the front of the flame gradually heat the gas. This case is the closest to that discussed in [3].

There are probably a number of other mechanisms; however, we can see from those we have enumerated that the assumption that constant volume heating takes place in the high pressure section is apparently not valid. If one of the mechanisms enumerated above is realized, then the efflux takes place at a temperature above that which occurs in the case of constant volume heating and, consequently, when calculating the velocity of the shock wave which forms in this case, for the velocity of sound we must use a value larger than $a_4/a_1 = 6$. Figure 1 shows that most of the points are located near Curve (2), which corresponds to $a_4/a_1 = 12$. The experimental result agrees with the data of [4, 5] in the sense that when computing shock wave velocities in a shock tube when OHHM is used in the high pressure section, we must use values for the velocity of sound which are significantly greater than the value computed on the assumption that heating at constant volume takes place in the high pressure section. An increase in the strength of the diaphragms leads to an increase in the shock wave velocity (under strictly equal conditions); however, a further increase in the strength of the diaphragms up to pressures significantly greater than one-half the computed values (according to the data of [3]) does not lead to a significant increase in the shock wave velocity.

Spectral Characteristics of Air

An overall schematic of the experiment is shown in Figure 2. Let us now present a brief description of the latter (a more detailed description is given in [1]).

An ISP-28 spectrograph and a UM-2 monochromator were placed facing each other so that the radiation of the gas would reach the input section of both instruments from that cross section of the shock tube located at a distance of 5 mm from the end face.

The spectrograph operated by scanning the spectrum. To do this we installed a special mechanism (described in more detail in [1]) which allowed us to obtain radiation spectra scanned over time every 30 μsec with a resolving power of 5 μsec. The spectral scans were interpreted using the method of heterochromatic photometry. In order to allow for the change in sensitivity of the film with wavelength, in addition to the radiation spectrum we photographed the spectrum of a standard light source: a tungsten filament lamp (type SI-10-300). Microphotographs were obtained using a type MF-4 microphotometer.

For the blackening distribution in the spectrum of the gas under examination:

$$S_1(\lambda) = \gamma(\lambda)\log\left[kl_1^{p_1}\left(\frac{d\lambda}{dl}\right)\varkappa_1(\lambda, T_1)B(\lambda, T_1)\right] - \gamma(\lambda)j(\lambda).$$

For the blackening distribution in the spectrum of the standard

source: /17

$$S_2(\lambda) = \gamma(\lambda) \log\left[kt_2^{p_2}\left(\frac{d\lambda}{dl}\right)\varkappa_2(\lambda, T_2)B(\lambda, T_2)\right] - \gamma(\lambda) j(\lambda),$$

for which we obtain

$$\frac{S_1(\lambda) - S_2(\lambda)}{\gamma(\lambda)} = \log\left[\frac{\varkappa_1(\lambda, T_1)}{\varkappa_2(\lambda, T_2)} \cdot \frac{B(\lambda, T_1)}{B(\lambda, T_2)}\right] + \log \frac{t_1^{p_1}}{t_2^{p_2}}.$$

Here $\kappa_1(\lambda, T_1)$, $\kappa_2(\lambda, T_2)$ are the degree of blackness of the gas and the standard source, respectively; $B(\lambda, T_1)$, $B(\lambda, T_2)$ are the emitting powers of a black body at the temperature of the gas and the temperature of the standard source; $\gamma(\lambda)$ is the contrast coefficient of the film; $j(\lambda)$ is the sensitivity of the film; p is the Schwarzchild constant; t_1, t_2 are the exposure times; k is the proportionality factor which is not a function of the properties of the substance or the wavelength, but an instrumental constant.

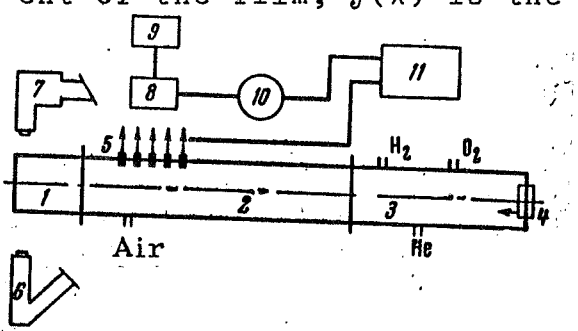

Fig. 2. Overall Schematic of the Experiment. (1) Optical Section; (2) Low Pressure Section; (3) High Pressure Section; (4) Device for Igniting the Mixture in the High Pressure Chamber; (5) Sensor for Measuring Shock Wave Velocity; (6) Type ISP-28 Spectrograph; (7) Type UM-2 Monochromator; (8) Type FEU-29 Photoelectric Multipliers; (9) High-Voltage Rectifiers; (10) Type I0-4 Oscillograph; (11) Synchronization Unit.

It follows from the last relationship that if we know the temperature of the gas under study, then we can determine the absorption coefficient of the gas as a function of wavelength with an accuracy up to a constant factor. The latter was determined using a photoelectric channel in which we placed a ZMR-3 monochromator and a FEU-29 photomultiplier. The channel was graduated in absolute units using a standard light source, a tungsten filament lamp (type SI-10-300). Since the temperature of the gas, heated by a reflected shock wave, can be computed according to the velocity of the incident shock wave, then using Kirchhoff's law we can determine the /18 absorbent power of the gas at a given wavelength. By taking advantage of the Beer law we can obtain a value for the absorption coefficient and normalize the relative function relating the absorption coefficient and wavelength, which we obtained above, throughout the spectral range under investigation.

Figures 3 and 4 show the values for the absorption coefficient measured in this way (Curve 1). The figures show all the values for the absorption coefficient of air heated by a reflected shock wave. These values were obtained by direct measurement of the blackening of the spectrograms. The continuous lines (1) show the values of

the absorption coefficient for air. The vertical lines show the

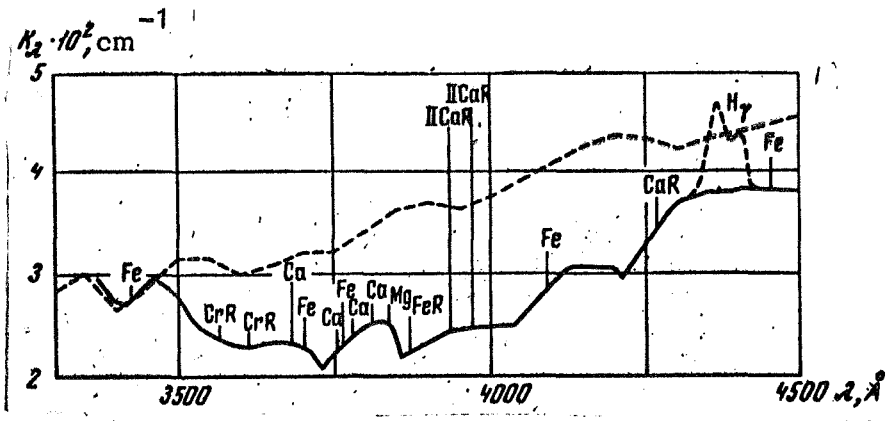

Fig. 3. Comparison of the Experimental and Calculated Indices of Absorption for Air at T = 13,500°K, p = 23 atm. ——— Experimental Data; ------ Calculated Data.

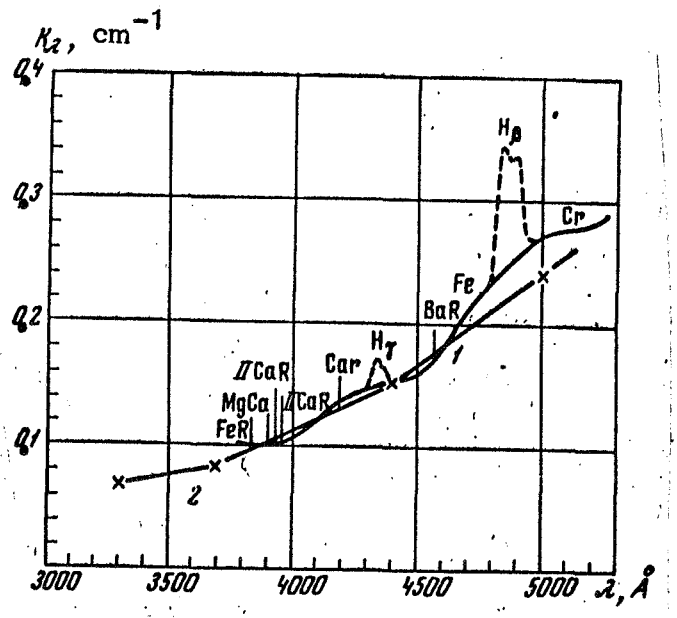

Fig. 4. Comparison of the Experimental and Calculated Indices of Absorption for Air at a Temperature of 17,000°K and a Pressure of 28 Atm According to the Data of [7, 8]. (1) Experimental Data; (2) Calculated Data.

values of the absorption coefficient measured at those points of the spectrum where the mixture lines lie. The height of each vertical line corresponds to the value of the absorption coefficient, measured directly at a given point of the spectrum. The mixture lines detected in the radiation spectra of air are given in the table.

Discussion of the Results

The experimental results obtained were compared with the calculated data. Figures 3 and 4 (Curves 2) show the values of the absorption coefficient of air calculated for the conditions corresponding to the experimental conditions. Here we take into account the absorption caused by free-free (according to the Kramers theory) and free-bound (according to [7]) electron transfers in the ion fields. For an air temperature of 14,500°K, we took into account absorption caused by the first negative system of a molecular ion of nitrogen $N_2^+(1-)$. The function relating the matrix element of the dipole moment of the electron transfer and

Wavelength, Å	Element I or Its Ion II	Excitation Energy, eV	Wavelength, Å	Element I or Its Ion II	Excitation Energy, eV
4861,3	H_β	12,74	3968,0	Ca II R	9,22
4603,0	Fe I	4,18	3933,7	Ca II R	9,26
4554,0	Ba II	7,9	3838,3	Mg I	5,94
4454,0	Ca I	4,68	3832,3	Mg I	5,94
4435,0	Ca I	4,68	3829,4	Mg I	5,94
4404,8	Fe I	4,68	3860,0	Fe I R	3,21
4340,5	H_γ	13,01	3737,0	Ca II R	12,57
4325,8	Fe I	4,47	3720,0	Fe I R	3,32
4318,7	Ca I	4,77	3706,0	Ca II R	12,57
4302,5	Ca I	4,78	3630,7	Ca I	5,30
4226,7	Ca I R	2,93	3505,3	Cr I R	3,43
4143,9	Fe I	4,55	3881,2	Fe I R	4,32
4071,7	Fe I	4,65	3578,7	Cr I R	3,46
4045,8	Fe I	4,55			

the r-centroid was taken according to the data of [8]. Its analytic form is /19

$$R_e = 5{,}04r^2 - 12{,}68r + 8{,}49, \quad 0{,}985\,\text{Å} < r < 1{,}30\,\text{Å}.$$

As we can see from Figures 3 and 4, there is satisfactory agreement between the experimental and calculated data within the margin of measurement error which was ± 20% when measuring the absorption coefficients using the heterochromatic photometry method and ± 25% with absolute photoelectric measurements. The agreement between the experimental and calculated data indicates the validity of the baseline data used in the calculation of the absorption coefficients and also allows us to conclude that there is a correlation between the real parameters of air heated by a reflected shock wave and the parameters computed according to the velocity of an incident shock wave.

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